Consequences of a Local Coincidence for a Large Array in Ice

III. Monte Carlo Simulations

J. Jacobsen and R.G. Stokstad

October 24, 1997

Abstract

Monte Carlo simulated events for a rectangular ICE^3 geometry are analyzed with a software filter to determine the local coincidence efficiencies for hits and events. Three energies (0.1, 1, 10 TeV), three string separations (100, 125, 150 m), and three vertical OM spacings (12, 16, 20 m) are considered. The coincidence efficiencies vary with these parameters, but relatively slowly. A local coincidence employing next-nearest-neighbor coincidences and a look-back procedure would, in all cases, preserve more than 92% of all events having five or more hits, and more than 99% of events having five or more direct hits. At the same time the local coincidence would, by suppressing tube noise, reduce the data rate to the surface by a factor of 250. Incorporating a local-coincidence in a first-level trigger also acts as a hit filter, enhancing both the fraction of direct hits sent to the surface, and the fraction of events having 5 or more direct hits. The local coincidence efficiencies obtained from the '97 B-10 data and the Monte Carlo simulation of these data are in good agreement. This suggests that the Monte Carlo estimates of local coincidence efficiencies for the ICE^3 geometries are reliable.

I. Introduction

This study, the third in a series of three reports (Refs. 1,2), is motivated by the advantages for a km-scale array of optical modules offered by a digital data collection system with high efficiency and low bandwidth requirements. A local coincidence is an integral part of a digital system under consideration for ICE^3 (Ref. 3), and it is important to assess as quantitatively as possible the consequences of incorporating it in the operation of an array. The availability of Monte Carlo simulations for ICE^3 (Ref. 4) provides an opportunity to study the effects of taking a local coincidence in a realistic situation. One can apply the local coincidence to the Monte Carlo with a software filter. It enables us to answer the following rather general questions.

1. What fraction of all hits participate in a local coincidence?

2. What fraction of all events is retained if a local coincidence is required?

3. What fraction of all direct hits participate in a local coincidence?

4. What fraction of events having 5 or more direct hits is retained if a local coincidence is required?

5. How important is a "look-back," a procedure through which hits not participating in the local coincidence are retrieved?

6. How does the coincidence efficiency vary with the energy of the muons and the geometrical parameters of the array.

The best way to convey the effects of a local coincidence is to take one set of events and analyze it with a single but realistic set of parameters. We do this to answer questions 1-5, and then vary parameters to study the effects of energy, string spacing, and OM spacing. In each case, the program "filt" (Ref. 5) was used, with options to invoke requirements on local coincidence, number of direct hits, and multiplicities of surviving hits.

II. The base data set

The Monte Carlo simulations used here were presented at the ICE^3 Neutrino Facility Workshop, March 27-28, 1998 (Ref. 4). Single muons were simulated at energies of 0.1, 1.0, and 10 TeV isotropically in a homogenous volume containing the array. Full stochastic energy loss for the muons was included. All events having 8 or more hits were retained. The direct hits were determined by using the track of the generated muon rather than a reconstructed track.

We consider first Monte Carlo simulations for 1 TeV muons and a rectangular array (minus the corner strings) on a 125 m grid, with 77 strings having 63 OMs per string, spaced at vertical intervals of 16 m, for a total of 4851 OMs.

The geometry is shown in Fig. 1.

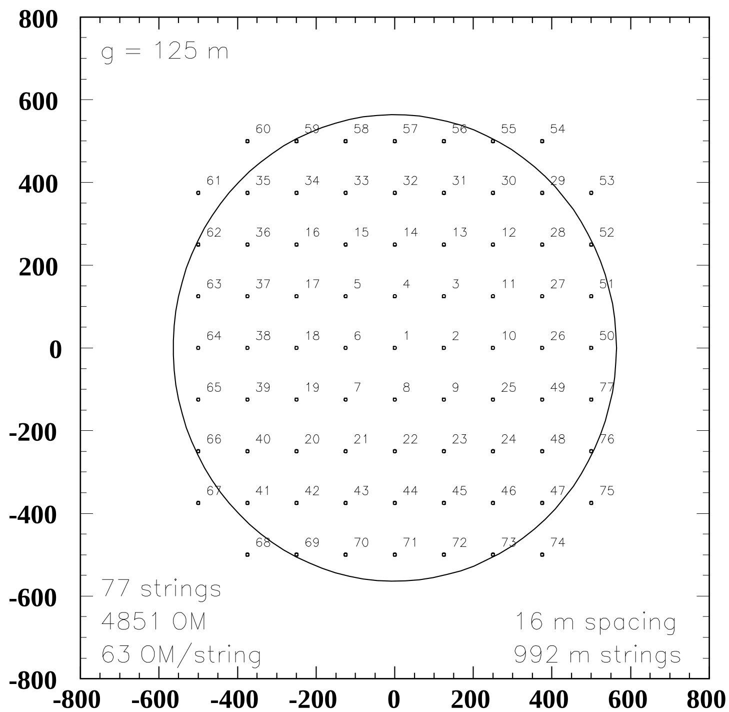

Fig. 1. Plan view of a rectangular array (minus the corner strings. (Ref. 4.)

This "data set" has the following properties:

Table 1

Data Set	Events	Hits	Direct Hits
Base(M8)	43246	939181	75797

A direct hit is one that is not "too early" (not more than 5 ns before) or "too late" (more than 25 ns after) the arrival time of an unscattered photon originating along the track of the reconstructed muon. "Hits" refers to the total number of hits and is the sum of direct hits and hits that arrived outside the interval from –5 to +25 ns.

III. Operation of an array using a local coincidence

An array using a local coincidence and a look-back procedure would likely be operated in the following manner described below. While the actual parameters used might vary, the parameters chosen here are considered representative and sufficient to illustrate the performance of a local coincidence.

A hit is in local coincidence if any one of three possibilities is satisfied:

i. The same OM receives another hit within 1000 ns (self coincidence).

ii. An adjacent OM receives a hit within 1000 ns. (nearest neighbor).

iii. An OM once removed receives a hit with 1000 ns. (next-nearest neighbor).

Only hits in local coincidence are initially digitized and sent to the surface. These time-stamped events are reviewed by a fast processor and an event is built whenever 5 or more hits arrive within a single period of 2-3 microseconds. As soon as an event is established, a track is fit to the hit pattern by a simple but fast algorithm and an instruction sent to all DOM's within a certain distance of that track to digitize and send up any hits it may have recorded within 1000 ns of the time calculated for an unscattered photon to arrive at that DOM. For the present analysis, we assume that this look-back procedure recovers all hits that did not participate initially in the local coincidence. (Different algorithms for locating hits in a look-back can also be studied using these MC events.)

Once all the hits in an event are assembled, the event can be stored for later analysis or perhaps first examined with a filter and then stored only if there is an enhanced likelihood that it was not a down-going cosmic-ray muon. In either case, subsequent off-line analysis would employ a cut on the minimum number of direct hits, which we take to be 5 or more. Thus, what counts ultimately is the fraction of those select events (i.e., those initially having 5 or more direct hits in the base data set) that are retained by the local-coincidence-plus-look-back procedure and are therefore available for analysis.

With a 1 kHz tube noise rate, a 1 microsecond coincidence window, and next-nearest neighbor coincidences, the rate at which noise hits are sent to surface is reduced by a factor of 250 compared to not having a local coincidence. This factor is inversely proportional to the width of the coincidence window and the tube noise rate.

IV. Results

We revisit our initial questions:

1. *What fraction of all hits participate in a local coincidence?*
2. *What fraction of all events is retained if a local coincidence is required?*
3. *What fraction of all direct hits participate in a local coincidence?*

In each case, we summarize the result in a table and then discuss the details.

Table 2

Data Set	Events	Hits	Direct Hits
Base(M8)	43246	939181	75797
Base⇒LC⇒M5	41314	603213	56271

The operations on the base are indicated in order, from left to right. The base was filtered with a local coincidence; all events having 5 or more hits participating in a local coincidence were passed. 41314 (95.5 %) of the events in the base set passed. These 41314 events contained 603213 coincidence hits and 56271 coincident direct hits. Thus, for the parameters here (M5, 1000 ns coincidence window), 64% of all hits and 74% of the direct hits in the base set participated in the local coincidence and were sent to surface as a part of the lowest level trigger. The hits that were not in local coincidence would then be recovered in the look-back procedure. 4.5 % of the base events had less than 5 coincident hits and are not recoverable. (But we wouldn't want most of these lost events, anyway, as we shall see next.)

4. What fraction of events having 5 or more direct hits is retained if a local coincidence is required?

Table 3

Data Set	Events	Hits	Direct Hits
Base⇒MD5	1371	45857	7762
(Base⇒MD5) ⇒LC⇒M5	1369	33170	7013

The first row states that the subset of events in the base that have at least 5 direct hits (MD5) contains 1371 such events, or 3.2% of the events in the base. These MD5 events contain a total of 45857 hits, of which 7762 are direct.

In the second row, we have performed the following operation. These 1371 events having MD5 were subjected to a local coincidence requirement. All those events that contained 5 or more hits (M5) were passed. Note that only 3 out of 1371 events were NOT retained. The important point here is that we require only 5 ordinary hits participate in a local coincidence for retention of the event, and not 5 direct hits. This is because it is 5 ordinary coincidence hits that cause an event to be built on surface. The look-back then recovers the isolated hits (ordinary and direct) that did not participate in the local coincidence. Thus, the look-back would recover approximately 75797 – 56271, or ~20000 total hits, and 7762 - 7013 = 749 direct hits.

5. How important is it to have a "look-back?"

If we don't have a look-back but still require that there be 5 direct hits to analyze an event, then there must be at least 5 direct hits participating in a local coincidence for an event to be retained.

Table 4

Data Set	Events	Hits	Direct Hits
Base⇒MD5	1371	45857	7762
(Base⇒MD5) ⇒LC⇒M5	1369	33170	7013
(Base⇒MD5) ⇒LC⇒MD5	997	25617	5667

The bottom row corresponds to the operation in which an event is retained only if there are 5 or more *direct* hits participating in a local coincidence. In this case, the retained fraction (of events in the base having 5 or more direct hits) is 997 / 1371 = 0.73. Thus, adding a look-back recovers for analysis the 27% of MD5 events that otherwise would have been lost because some of the direct hits did not make a local coincidence.

Combining all the results into one table, we have:

Table 5

Data Set	Events	Hits	Direct Hits
Base(M8)	43246	939181	75797
Base⇒LC⇒M5	41314	603213	56271
Base⇒MD5	1371	45857	7762
(Base⇒MD5) ⇒LC⇒M5	1369	33170	7013
(Base⇒MD5) ⇒LC⇒MD5	997	25617	5667

To summarize at this point, a local coincidence operating with parameters as described above (including a look-back) would for this simulation of 1 TeV muons in an ICE^3 array:

i. reduce the data rate to the surface by a factor of 250 (the elimination of tube noise)
ii. preserve 95.5% of all events having 5 or more hits.
iii. preserve 99% of the events having 5 or more direct hits.

Furthermore, we see that the look-back is an important feature and should be included in the design of the system.

V. Variation of efficiency with array parameters.

A. Energy

Table 6 gives the results obtained at 0.1 TeV, 1 TeV, and 10 TeV for one particular configuration (125 m string spacing, 16 m OM vertical spacing, 4851 OMs).

Table 6. Results for different energies

	0.1 TeV events	125 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	50922	889591	86014	0.097				
2	47156	530619	59294	0.112	2/1	0.926	0.596	0.689
3	1127	29174	6209	0.213	3/2	0.024	0.055	0.105
4	1127	20909	5523	0.264	4/3	1.000	0.717	0.890
5	765	15685	4234	0.270	5/4	0.679	0.750	0.767
	1 TeV events	125 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	43246	939181	75797	0.081				
2	41314	603213	56271	0.093	2/1	0.955	0.642	0.742
3	1371	45857	7762	0.169	3/2	0.033	0.076	0.138
4	1369	33170	7013	0.211	4/3	0.999	0.723	0.904
5	997	25617	5667	0.221	5/4	0.728	0.772	0.808
	10 TeV events	125 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	54558	2263416	121604	0.054				
2	53896	1674668	103022	0.062	2/1	0.988	0.740	0.847
3	5063	348907	29951	0.086	3/2	0.094	0.208	0.291
4	5063	270890	27556	0.102	4/3	1.000	0.776	0.920
5	4048	223664	23774	0.106	5/4	0.800	0.826	0.863

Row key:
1 Base(M8)
2 Base⇒LC⇒M5
3 Base⇒MD5
4 (Base⇒MD5) ⇒LC⇒M5
5 (Base⇒MD5) ⇒LC⇒MD5

Each of the five rows that follows an energy heading corresponds to the five rows in Table 5. That is, the first row is the "base" data set, the second row has the local coincidence applied with M5, the third row corresponds to events that contain 5 or more direct hits, and so on. The fifth *column* gives the ratio of direct hits to total hits for values in each row. The event, hit, and direct hit ratios in columns 6-8 have the numerator taken from the same row and the denominator from the row just above, as indicated by the notation 2/1, 3/2, ec.

As one would expect, the local coincidence efficiency for hits and events, as expressed by the ratios in columns 6-8, increases with energy. The main difference occurs in the ratio of local coincidence hits to total hits, (row 2, column 7), which rises from 0.596 at 0.1 TeV to 0.740 at 10 TeV. However, the fraction of events in the base containing 5 direct hits, which are retained by the local coincidence (including a look-back), is >99% in all cases (row 4, column 6).

It is interesting to note that the fraction of total hits that are direct (column 4) decreases with increasing energy (form 0.097 to 0.054). We may speculate that the reason for this is the larger amount of Cherenkov light originating with showers or "brems" at the higher energies. These photons are less likely to be emitted at exactly 42 degrees to the muon track and so will experience a longer time in flight compared to that calculated for unscattered photons that were emitted at the Chernkov angle.

B. String spacing

Table 7 shows the results obtained at one energy (1 TeV) for three different string spacings, viz., 100m, 125m, and 150m.

The critical local coincidence efficiencies are essentially independent of the string spacing over the range of variation examined here. A quantity that does vary significantly, however, is the fraction of MD5 events contained in the total number of events (even before any local coincidence is applied.) A smaller string spacing leads to a larger fraction of 5-direct hit events in the base. (The variation is from 0.023*(0.961) at 150 meters to 0.061*(0.960) at 100 meters.) This may simply be a consequence of the, on average, greater distance photons must travel to reach the OM's as the string spacing increases from 100 to 150 meters. This trend is continued in the results for the '97 data, where the string spacing is typically 50 meters, and the MD5 fraction rises to 0.211*(0.973) (see Table 9). Note that the actual number of direct hit events is the product of the direct hit fraction and the effective area of the array for all events. So the large array will likely produce a greater number of MD5 events per unit observation time.

Table 7. Results for different string spacings

	1 TeV events	100 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	37110	985538	74197	0.075				
2	35615	627344	55328	0.088	2/1	0.960	0.637	0.746
3	2182	90009	12596	0.140	3/2	0.061	0.143	0.228
4	2180	62421	11061	0.177	4/3	0.999	0.693	0.878
5	1508	46186	8675	0.188	5/4	0.692	0.740	0.784
	1 TeV events	125 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	43246	939181	75797	0.081				
2	41314	603213	56271	0.093	2/1	0.955	0.642	0.742
3	1371	45857	7762	0.169	3/2	0.033	0.076	0.138
4	1369	33170	7013	0.211	4/3	0.999	0.723	0.904
5	997	25617	5667	0.221	5/4	0.728	0.772	0.808
	1 TeV events	150 m hits	16 m direct hits	(dir hits)/hits		event ratio	hit ratio	dir hit ratio
1	44802	849871	73039	0.086				
2	43050	558919	55436	0.099	2/1	0.961	0.658	0.759
3	994	28327	5501	0.194	3/2	0.023	0.051	0.099
4	993	21266	5047	0.237	4/3	0.999	0.751	0.917
5	732	16654	4081	0.245	5/4	0.737	0.783	0.809

Row key:
1 Base(M8)
2 Base⇒LC⇒M5
3 Base⇒MD5
4 (Base⇒MD5) ⇒LC⇒M5
5 (Base⇒MD5) ⇒LC⇒MD5

C. OM spacing.

Here again, the important local coincidence efficiencies do not vary much in these three cases where the OM vertical spacing is changed from 12 to 20 m. The fraction of MD5 events that are recovered when a local coincidence is applied (and a look back) is unity. However, the same trend toward a smaller fraction of MD5 events in the total number of events is present here, where the MD5 event fraction at a 20m spacing (0.022*0.993) is about half the value at 12m (0.049*0.996). The same speculation - a larger average photon travel distance with a larger spacing - can be made here as well.

<u>Table 8. Results for different OM spacings</u>

	1 TeV events	125 m hits	12 m direct hits	(dir hits)/hits		event ratios	hit ratios	dir hit ratios
1	12544	309118	24244	0.078				
2	12497	258734	22216	0.086	2/1	0.996	0.837	0.916
3	616	23335	3531	0.151	3/2	0.049	0.090	0.159
4	616	20445	3430	0.168	4/3	1.000	0.876	0.971
5	561	18851	3214	0.170	5/4	0.911	0.922	0.937
	1 TeV events	125m hits	16 m direct hits	(dir hits)/hits		event ratios	hit ratios	dir hit ratios
1	43246	939181	75797	0.081				
2	41314	603213	56271	0.093	2/1	0.955	0.642	0.742
3	1371	45857	7762	0.169	3/2	0.033	0.076	0.138
4	1369	33170	7013	0.211	4/3	0.999	0.723	0.904
5	997	25617	5667	0.221	5/4	0.728	0.772	0.808
	1 TeV events	125 m hits	20 m direct hits	(dir hits)/hits		event ratios	hit ratios	dir hit ratios
1	14237	282514	23529	0.083				
2	14138	218408	20088	0.092	2/1	0.993	0.773	0.854
3	307	9382	1705	0.182	3/2	0.022	0.043	0.085
4	307	7885	1620	0.205	4/3	1.000	0.840	0.950
5	253	6836	1417	0.207	5/4	0.824	0.867	0.875

Row key:
1 Base(M8)
2 Base⇒LC⇒M5
3 Base⇒MD5
4 (Base⇒MD5) ⇒LC⇒M5
5 (Base⇒MD5) ⇒LC⇒MD5

D. The Local Coincidence as a filter.

The local coincidence acts as a filter that enhances the information content of the hits and events that are transmitted to surface. Column 5 of Table 6 shows how the fraction of direct hits increases as the local coincidence is applied. Thus the information available for an event in the initial set of hits (the coincidence hits sent to surface) is richer – it has a higher direct hit content – than the event will have afterward, when the look-back is instituted. Simply said, direct hits are more likely to participate in a local coincidence, which is an intuitively reasonable result. The same trend was found in the data and is discussed in Ref. 2. The effectiveness of the local coincidence increases with multiplicity.

E. Variation with multiplicity.

The above calculations have been done with a local coincidence multiplicity requirement of 5 in order to determine under realistic circumstances the maximum fraction of events and hits that survive a local coincidence trigger. That may not be an optimum multiplicity, however. Raising the multiplicity will enable the local coincidence to act more effectively as a filter in preferentially passing the events that contain 5 direct hits.

Figure 2 shows the ratio of all events that pass a local coincidence with the indicated multiplicity to the events in the base set that have that same multiplicity.

The losses are, as expected, dependent on the energy of the muons, with 100 GeV muons having the largest number of events that do not survive. However, the picture is

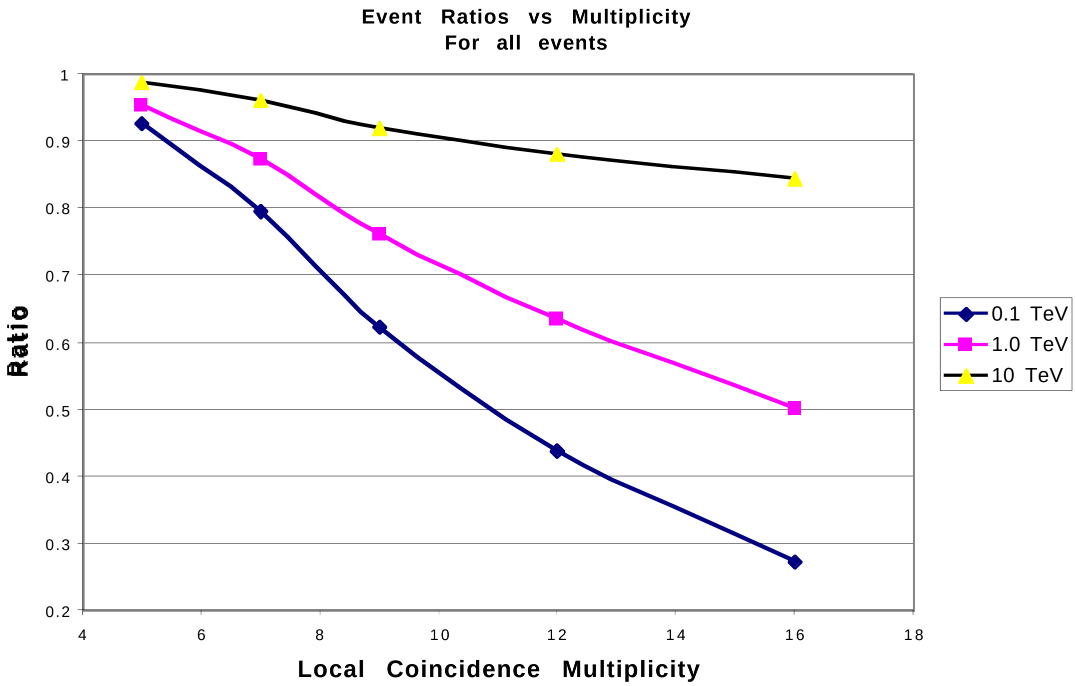

Fig. 2. Ratio of all events that pass a local coincidence with the indicated multiplicity to the events in the base set that have that same multiplicity.

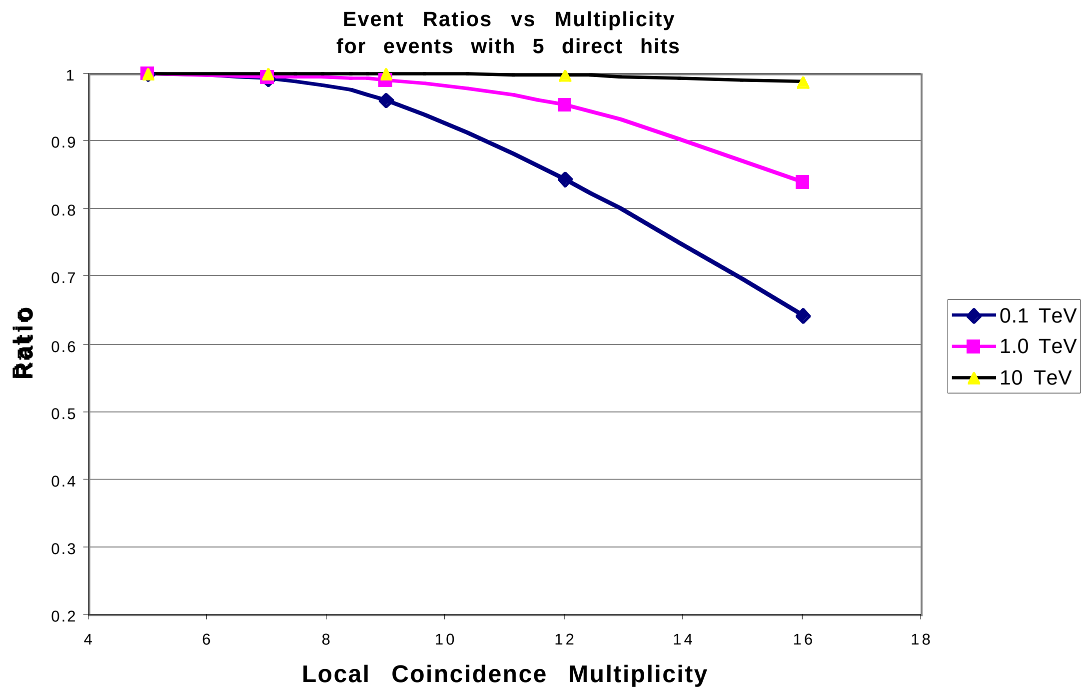

Figure 3. Ratio of all MD5 events that pass a local coincidence with the indicated multiplicity to the MD5 events in the base set that have that same multiplicity.

quantitatively quite different when only those events having 5 direct hits or more are considered.

If we take those Monte Carlo events that have at least 5 direct hits and a minimum total hit multiplicity M, and ask what fraction of these events will pass a local coincidence trigger when we require that there be M or more hits that participate in a local coincidence, we obtain the results shown in Fig. 3.

The losses are much less for the 5-direct-hit events. In fact, multiplicity 12 could represent a more optimal operational configuration in that the losses (compared to "singles" operation) are only 5 % for 1 TeV muons. Yet, the number of events to process will be reduced by 37% and the total number of hits by 49%. These savings in the number of events to process are relative to what would have to be processed with an ordinary 12-fold majority logic requirement. That is, they are over and above the reductions in events and hits that occur when raising the multiplicity from 5 to 12.

F. Comparison with the '97 Data and Monte Carlo.

The analysis shown in Table 9a is based on experimental data that were acquired with a majority logic trigger of 16 hits. After hit cleaning, a multiplicity of 12 hits was required. Other details of the analysis of these data are found in Ref. 2.

The Monte Carlo events (Table 9b) of the '97 B-10 data were taken from the current first-pass mass-production of B-10 MC runs with "amasim2 "in Stockholm and Zeuthen, and were reconstructed using the program ""recoos. The same OM's that were removed from the data stream were also removed from the Monte Carlo events.

The main difference between the data and the simulation is the higher fraction of direct hits in the data and events with 5 direct hits. (This is also true if we compare the data with the more schematic caluclations in Ref. 1. The local coincidence efficiencies, however, are similar for data and Monte Carlo. These are the ratios in the rows indicated by "2/1" and "4/3." This strongly suggests that the Monte Carlo estimates of local coincidence efficiencies for the ICE3 geometries are reliable.

Table 9. '97 B-10 Data and Monte Carlo

a)	97 Data	~50m	~14m	273 OMs				
	events	hits	direct hits	(dir hits)/hits	event ratios		hit ratios	dir hit ratios
1	13746	354216	43926	0.124				
2	13372	228514	36502	0.160	2/1	0.973	0.645	0.831
3	2815	83023	17713	0.213	3/2	0.211	0.363	0.485
4	2807	57206	15843	0.277	4/3	0.997	0.689	0.894
5	2113	47414	13388	0.282	5/4	0.753	0.829	0.845
b)	B-10 M.C							
	events	hits	direct hits	(dir hits)/hits	event ratios		hit ratios	dir hit ratios
1	13237	415824	29621	0.071				
2	13148	243061	23457	0.097	2/1	0.993	0.585	0.792
3	833	29085	4640	0.160	3/2	0.063	0.120	0.198
4	833	17796	4034	0.227	4/3	1.000	0.612	0.869
5	538	12820	3000	0.234	5/4	0.646	0.720	0.744

Row key:
1 Base(M12)
2 Base⇒LC⇒M5
3 Base⇒MD5
4 (Base⇒MD5) ⇒LC⇒M5
5 (Base⇒MD5) ⇒LC⇒MD5

The local coincidence efficiencies are rather similar even for an ICE^3 geometry and for a much smaller array size and number of OMs . **This shows the inherently robust nature of the local coincidence method.**

VII. Conclusions

We have used a series of Monte Carlo simulations for ICE^3 to study the expected performance of a local coincidence trigger in a digital optical module system. Here, also, we find that the local coincidence mode of operation is a powerful means of reducing noise and corresponding reduction of bandwidth requirement, with minimal or no loss of detector efficiency (effective area). A look-back scheme plays an important role to maintain the high efficiency of this method. The deduced local coincidence efficiencies are quite stable over a range of energy, string spacing, OM spacing, and total number of OMs. The results from the B-10 experimental data are rather similar to those obtained from a MC simulation for ICE^3, illustrating the robust nature of the method.

Acknowledgements

We are very grateful to Matthias Leuthold for running the Monte Carlo simulations used here. It is a pleasure to acknowledge his cooperation and help.

References:

1. Consequences of a Local Coincidence for a Large Array in Ice.
I.Schematic Calculations Using Probability Distributions
R. G. Stokstad, May 1, 1998 LBNL-41476
http://area51.berkeley.edu/manuscripts/

2. Consequences of a Local Coincidence for a Large Array in Ice.
II .Local Coincidences in AMANDA B-10 '97 Data
J. Jacobsen and R. G. Stokstad, October 9, 1998
http://area51.berkeley.edu/manuscripts/

3. Digital Optical Module & System Design for a Km-Scale Neutrino Detector in Ice.
D. Nygren, et al., March 20, 1998
http://area51.berkeley.edu/manuscripts/

4. "First steps towards an Ice-cube simulation," by S. Hundertmark, M. Leuthold, C. Spiering, and C. Wiebusch. ICE^3 Neutrino Facility Workshop, March 27-28, 1998. U.C. Irvine, Irvine, CA.

S. Hundertmark , PhD Thesis "Simulation und Analyse der Myonendaten des AMANDA-B4 Neutrinoteleskops," Humboldt Universitaet Berlin, 1998

5. filt: A program for selecting hits and events from AMANDA data in the F2000 format, by J. Jacobsen. In the "tools" CVS archive on alizarin.physics.wisc.edu.